UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Altered Volcanic Ash Partings in the C Coal Bed, Ferron Sandstone Member of the Mancos Shale, Emery County, Utah

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Open-File Report 81-[redacted]775

1981

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INTRODUCTION

When volcanic ash falls onto the surface of a peat-forming swamp and is then covered by peat, it forms a horizontal parting that can be recognized in the subsequent coal bed. As a consequence of the acid leaching environment in the swamp, the original glassy component and some of the less resistant pyrogenic minerals in the ash alter to clay minerals, usually kaolinite. The volcanic origin of such a clay-rich parting may be difficult to recognize in the field, but can be identified readily in the laboratory. Once identified, the altered volcanic ash parting can be a powerful aid in the stratigraphic, geologic and geochemical interpretation of coal beds. This report is a detailed study of some of these partings in an Upper Cretaceous coal bed in central Utah.

LOCATION AND STRATIGRAPHY

The Ferron Sandstone Member of the Mancos Shale was deposited during late Turonian time as a clastic wedge that represents northeastward progradation of a deltaic system into the Cretaceous seaway of the western interior (Cotter, 1975). It consists of five delta cycles, each of which contains one coal bed or coal zone (Fig. 1). The C coal bed lies above the delta-front sandstone of the third cycle and contains at least four prominent altered volcanic ash partings. Other partings may be present where the coal is thicker than usual, but these are considered insignificant because of their localized extent. The four consist of a thick upper parting (24-68 cm thick where the top hasn't been eroded), a pair (doublet) of thinner partings 3-43 cm apart and each from 3-10 cm thick, and a lower parting 4-20 cm thick. The intervals between these partings are variable and are shown in Table 1 (p. 15). A photograph of a C coal outcrop displaying these four prominent partings is shown in Fig. 2.

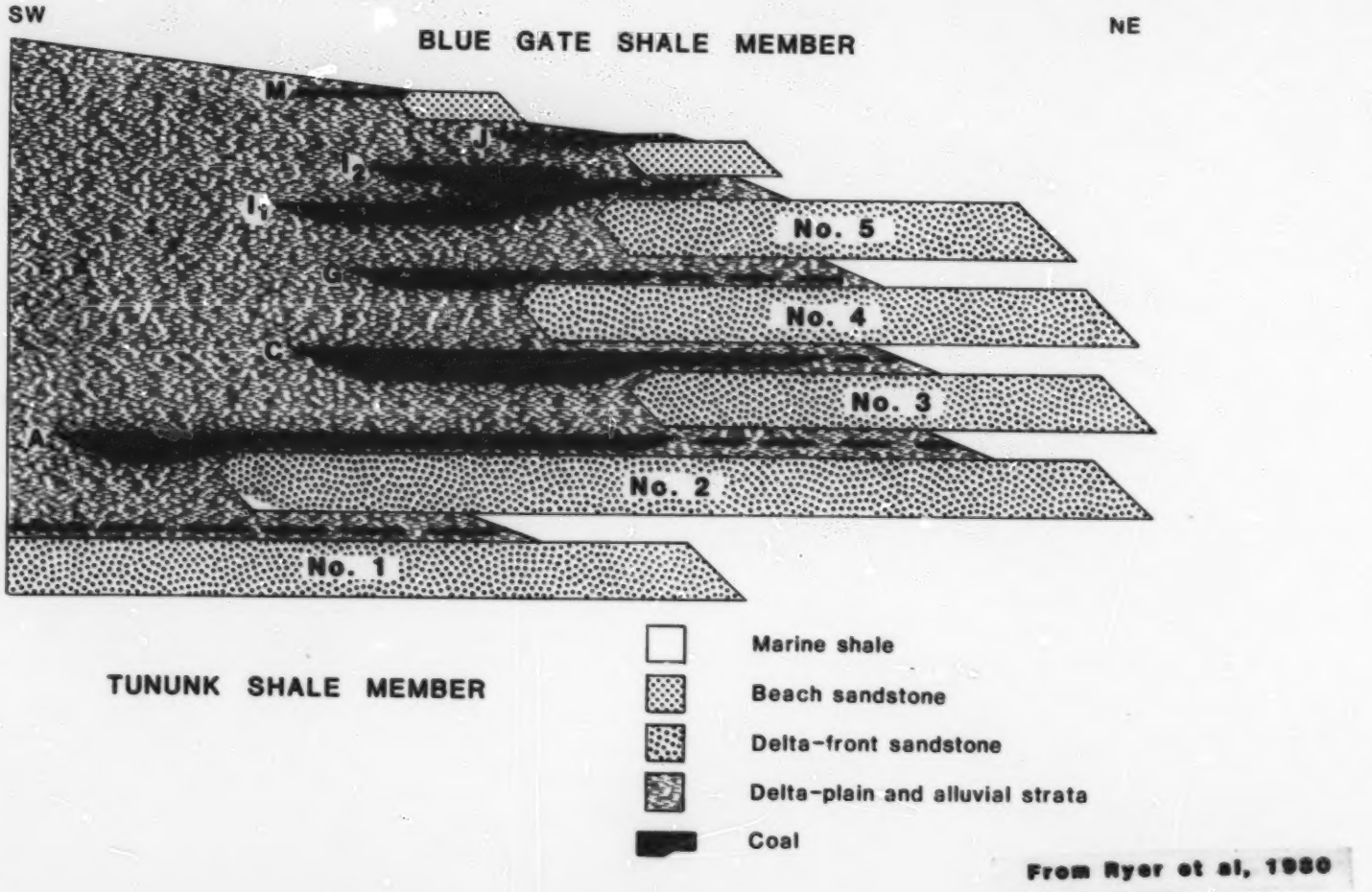

FIG. 1. SCHEMATIC CROSS-SECTION THROUGH FERRON SS. SHOWING COALS AND MARINE SANDSTONES ASSOCIATED WITH LAST CHANCE DELTA.

FIG. 2. C-COAL OUTCROP SHOWING 4 PARTINGS. OVERLAIN BY MARINE DELTA-FRONT SS.

Although some data on each of these 4 partings are included in this report, the doublet and the lowest parting were not studied in as great detail as was the thick upper parting, because these lower partings proved to involve less textural and mineralogical variation than the upper one. Whenever we mention the "thick" parting in this paper, we will be referring to the upper parting.

The subcrop of the C coal bed of the Ferron Sandstone Member in the southern Castle Valley, Utah, exhibits an elongate northeast-southwest trend on the gently dipping western limb of the San Rafael Swell, the anticlinal crest of which is to the east (Ryer and others, 1980). The C coal bed crops out along the Coal Cliffs, the eroded east-facing escarpment of this anticlinal limb, as well as in several canyons cut into the west-dipping slope of the Ferron Sandstone Member. The C coal bed can be traced on the outcrops for more than 20 km along this northeast-southwest trend of exposures. Fig. 3 is a location map showing the extent of the Ferron outcrop and the sampling localities where partings were collected for this report.

PREVIOUS WORK

The Ferron Sandstone Member was named by Lupton (1916). Bartram (1937) first suggested that it may be a delta, an idea later refined by the work of Davis (1954) and Katich (1954). Hale (1972) named this deltaic unit the "Last Chance Delta," and Cotter (1975, 1976) presented a detailed interpretation of its depositional environments and their relationship to coal formation in the Ferron.

Ryer (1979) studied the Ferron Sandstone Member as a predictive model for other deltaic Cretaceous coals of the Western Interior as part of a coal resources project of the U.S. Geological Survey (USGS). Building on this experience and framework, Ryer and others (1980) showed how altered volcanic

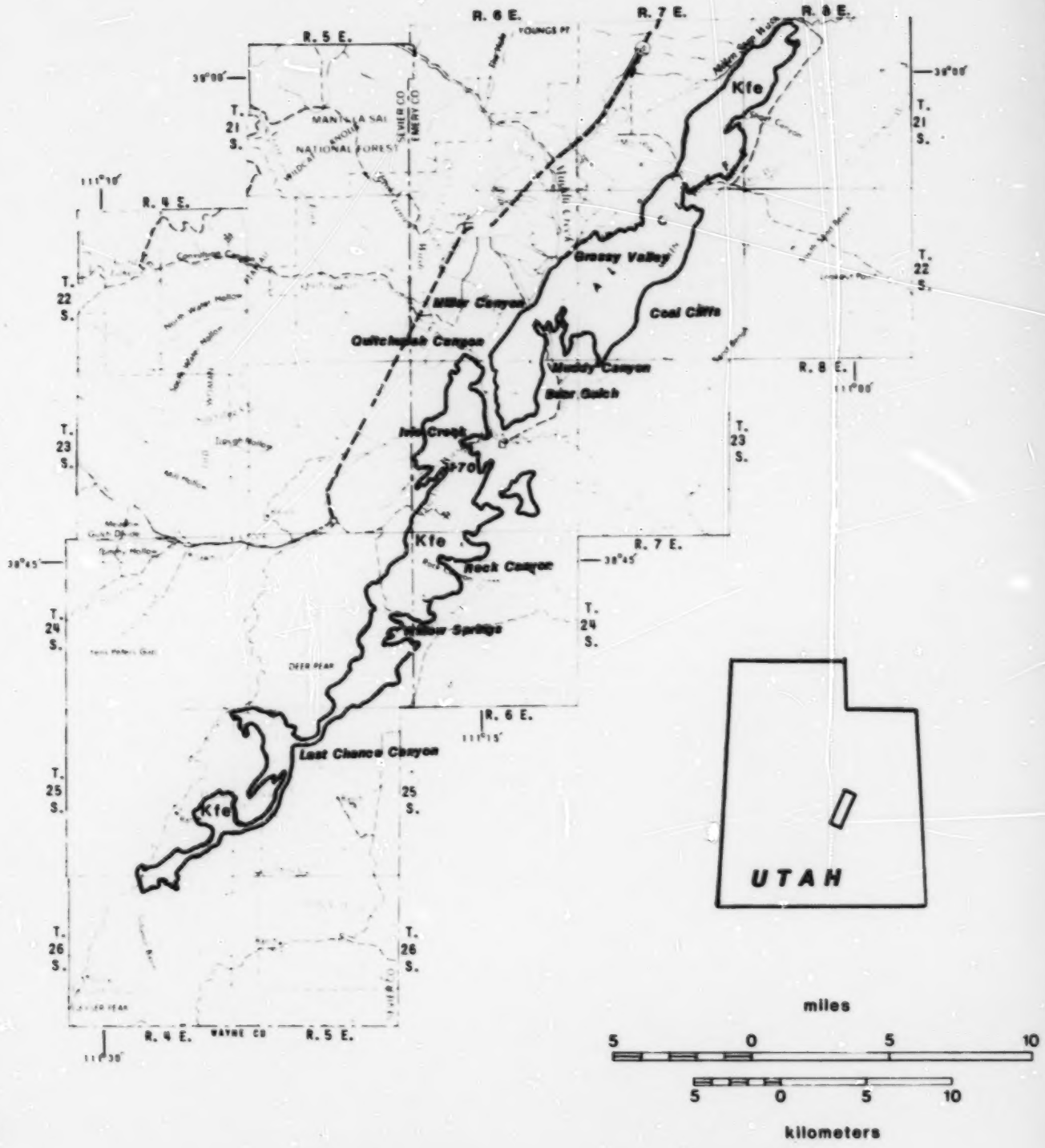

FIG. 3. FERRON OUTCROP AND SAMPLE LOCALITIES

ash partings in the C coal bed of the Ferron Sandstone Member could be used in stratigraphic studies of coal-bearing sequences. This latter study is the only work to date on the volcanic ash partings in the coals of the Ferron Sandstone Member. Figure 4 is from this paper and shows how the C coal bed can be vertically zoned using these partings.

METHODS OF INVESTIGATION

Field Investigations

An initial survey of partings in all the coal beds in the Ferron Sandstone Member was made during the summer of 1978. Field investigations of partings in the C coal bed of the Ferron took place during September, October, and part of November 1979. Further sample collections were made during May 1980.

Localities where samples of partings were taken from the C coal bed are shown in Fig. 3 (p. 5). Sample localities ranged from the Coal Cliffs east of Emery, near the seaward (distal) part of the No. 3 delta, to the canyon of Last Chance Creek, where the C coal bed pinches out into delta plain and fluvial strata. Just north of Last Chance Canyon, the thick upper parting of the C coal bed is found in a carbonaceous shale, the lateral fine-grained equivalent of the coal swamp. Actual sample stations are shown on plate 1.

The total number of samples of C coal bed partings collected for this report is 155. Of this number, 78 were samples of the thick upper parting, 48 were samples of the upper and lower members of the doublet, and 29 were samples of the lower parting. Because of its thickness, the thick parting occasionally was sampled in three parts--top, middle, and bottom.

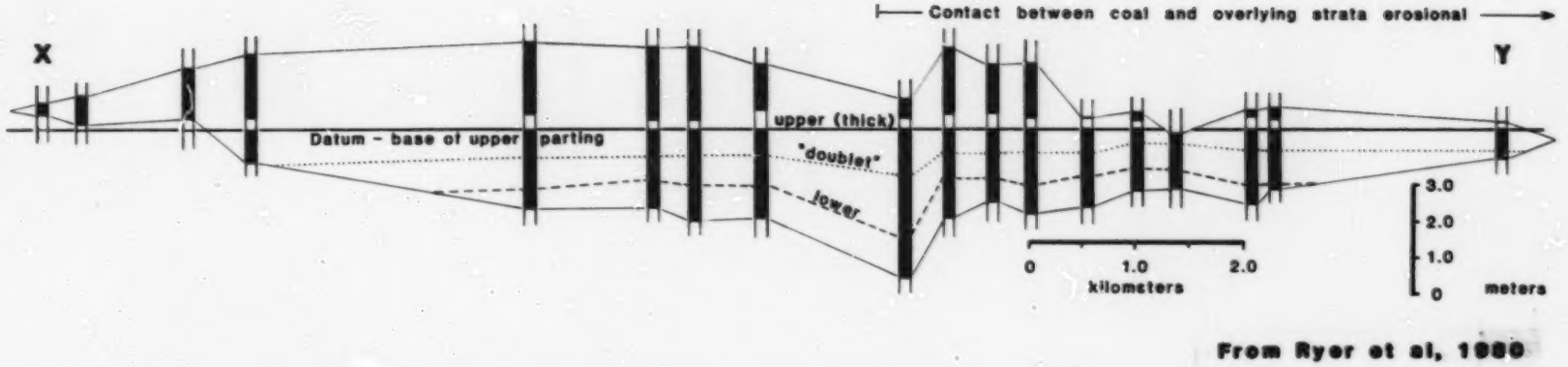

FIG. 4. CROSS-SECTION OF C COAL SHOWING ZONATION BY ALTERED ASH PARTINGS.

(Line of cross section shown on Plate 1)

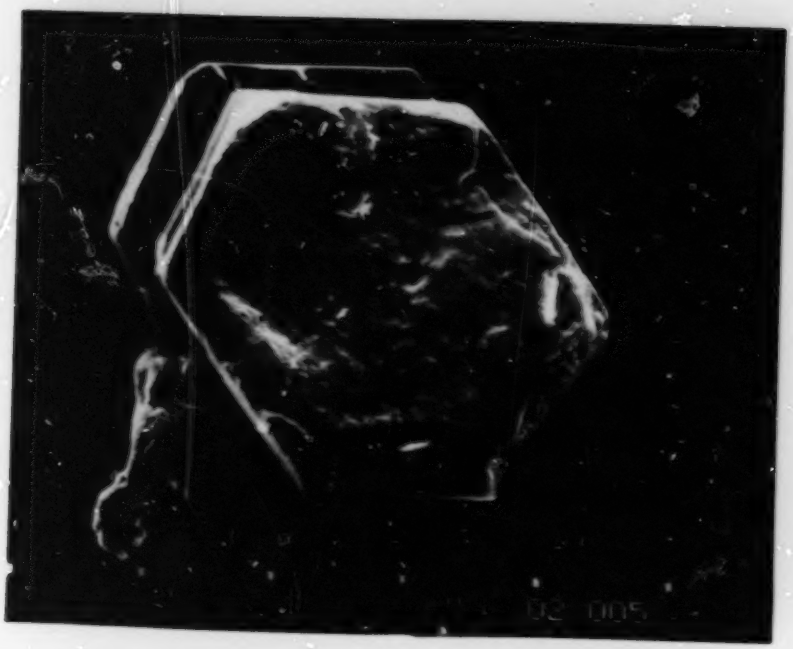

FIG. 5. ALTERED BIOTITE WITH KAOLINIZED RIM.

Tick marks are 100 microns apart

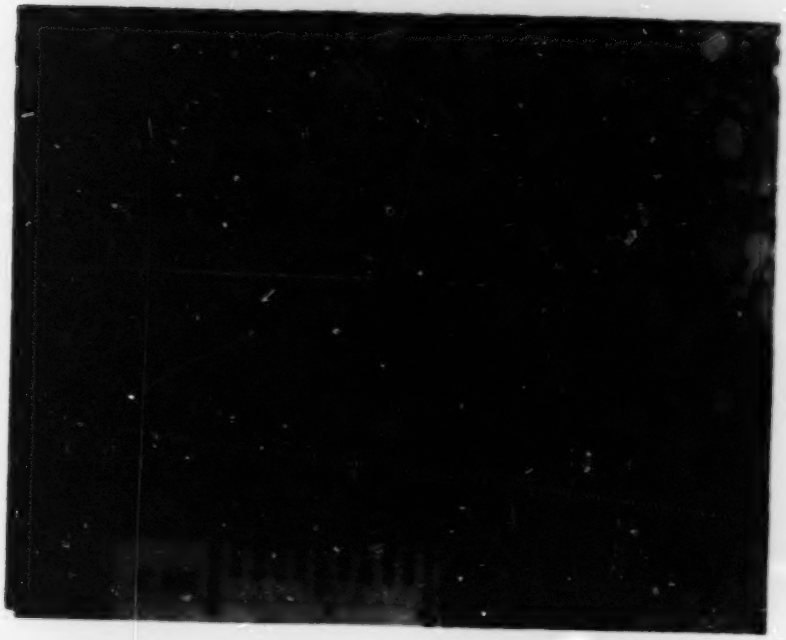

FIG. 6. GRAUPEN.

The general procedure of field investigation was: location of the outcrops on a 7 1/2-minute topographic quadrangle map; measurements of total coal thickness, intervals between partings, and thicknesses of individual partings; and collection of parting samples. Observations were made on the overlying and underlying units, particularly with respect to erosion of the top of the coal by fluvial or marine sandstones.

Many hand specimens of the partings were examined for texture in the field by sanding or scraping the surface smooth and then applying a thin coat of glycerine. This technique reveals details of texture not readily visible on a rough, broken surface, such as kaolinite vermicules, graupen (irregular fine-grained blebs of kaolinite), biogenic structures, accretionary lapilli, and the presence of bedding. Those samples not examined in this manner in the field were later smoothed with a power belt sander in the lab, and their textural features were examined with either a hand lens or a binocular microscope.

Laboratory Investigation

Laboratory analysis of samples collected in the field was accomplished by X-ray diffraction, binocular microscopy, petrographic microscopic examination of thin sections, and scanning electron microscopy (SEM).

X-ray diffraction--All samples collected in the field were analyzed by X-ray diffraction. Portions of each sample were crushed and ground to approximately 100 mesh with a jaw crusher and pulverizer, and then hand ground to a fine powder with a mortar and pestle. These powders were back-loaded into a holder and X-rayed from 4-40° 2θ in a diffractometer. This method of mounting produces preferred orientation of the clay minerals, enhancing their basal diffraction peaks. This factor was probably consistent for all the samples and is deemed desirable for identification of the clay minerals.

Some of the sample ground to 100 mesh was washed in a beaker to remove the clay minerals and organic matter (coal), concentrating a residue of non-clay crystalline material--the phenocrysts in the original volcanic ash that have not been altered to clay. A portion of the phenocrystic material was further ground to fine powder in a mortar. Double-back tape was placed on one surface of a glass microscope slide, the protective film peeled from the upper half, and this slide pressed onto the sample powder, which had been evenly distributed on a flat surface. A thin, continuous layer of powder adhered to the tape, and the slide was mounted so that this coated surface was exposed to the X-ray beam in the diffractometer.

The resulting X-ray pattern is quite similar to that of a bulk powder mount, but the samples are easier to prepare and require much less material. Usable patterns can still be obtained, even when the amount of sample is very small.

Microscope Examination--The washed residue prepared for X-ray diffraction, as described above, was washed into a Petri dish with distilled water and examined with a binocular microscope. If kaolinite vermicules or stacks of large kaolinite platelets were present in the original sample, they could not have been removed by simple elutriation and would have concentrated in the washed sample. In order to remove them without crushing the phenocrystic material, the wet sample was lightly ground in a mortar with a small rubber ball. This procedure disaggregates the vermicules and stacks into free kaolinite platelets, which can then be floated off.

Binocular examination of the washed samples has proven very useful in the study of altered volcanic ashes. One must use a fairly powerful microscope (ours gives a maximum of 80X magnification) with adequate sources of both incident and transmitted light. The washed sample can be "panned" in the

water-filled Petri dish, giving localized concentrations of heavy minerals such as zircon, ilmenite and magnetite. Highly refractive grains, such as -quartz crystals and zircons, are readily distinguishable, because refractivity is enhanced by the water medium. If individual grains need to be removed for further petrographic or SEM examination, the water can be evaporated and the grains removed with a probe.

Thin-section analyses--38 samples of the thick parting of the C coal bed were thin-sectioned and examined with a petrographic microscope. Although specific microtextural details can be discerned in thin-section, this technique has not proven as useful as examination of polished surfaces by binocular microscope or hand-lens or examination of washed samples by binocular microscope. An analogous technique that did prove useful was the preparation of grain mounts in liquids that had appropriate indexes of refraction to allow an easy distinction between quartz and feldspar.

CLAY MINERALOGY

Kaolinite

The clay mineral kaolinite comprises the major portion of all the altered volcanic ash partings. Some of the samples are essentially pure kaolinite. The morphology and grain size of kaolinite vary considerably; usually more than one type occurs in a given sample. Most common are microcrystalline to cryptocrystalline crystals that form a compact massive rock. The crystals are relatively equant in shape and often are arranged in short stacks of hexagonal platelets. Extended stacks (vermicules) are also common, and constitute the largest crystals in many samples.

Of particular significance are kaolinite pseudomorphs after biotite. All stages of the transition occur: from unaltered biotite, to flakes with a dark biotite core and a kaolinitic rim (Fig. 5), to silvery-white flakes that are entirely kaolinite. Many of the pseudomorphs are hexagonal and occur as

scattered large crystals in a finer grained matrix. Such crystals could easily be mis-identified as muscovite--a serious error, because the presence of muscovite would imply a terrigenous clastic origin.

Cryptocrystalline kaolinite also forms small lenses or blebs known as graupen (Fig. 6) ranging up to a few millimeters in diameter. They are not common in the Ferron Sandstone ash partings but are frequently reported from European tonsteins. Where present, most of the graupen are coarse; they are most abundant at the base of a unit and decrease in size upward. The origin of graupen is controversial, and the Ferron occurrences do not provide any basis for selecting between the suggested origins (e.g., pumice fragments, accretionary lapilli, clastic fragments, replaced rootlets or other plant fragments).

In addition to forming a structureless matrix, cryptocrystalline kaolinite also occurs as cavity fillings of wood cells and rootlet traces. Such kaolinite is obviously a relatively late feature that probably precipitated from solution.

X-ray diffraction characteristics of the kaolinite from all of the partings are relatively uniform. Fig. 7A shows a typical kaolin-rich sample with a minor amount of quartz. Such a kaolinite could be described as moderately well crystallized. One difference noted is variation in the intensity of the 003 peak relative to other members of the kaolinite "triplet" between 38° and 39.5° 2θ. This variation in intensity presumably reflects the degree of preferred orientation of platy particles, and thus could be used to identify the presence of platy kaolinite. In the thick parting, kaolinite 003 intensities are highly variable. However, most samples of the upper member of the doublet are characterized by relatively intense 003 itensities, whereas very few samples from the lower member of the doublet and the lower parting have this property.

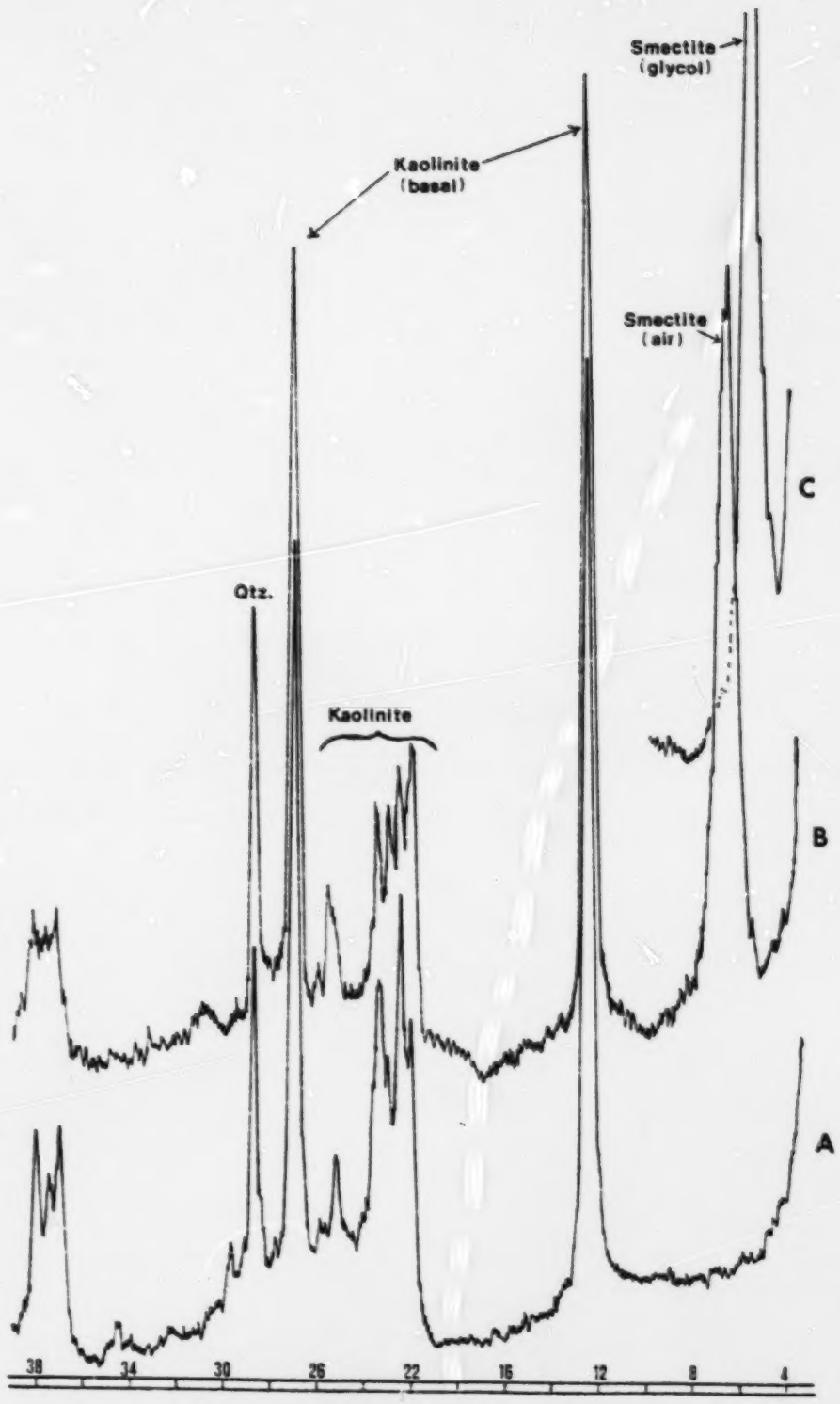

FIG. 7. X-RAY TRACES OF TYPICAL C-COAL PARTINGS.

Smectite (montmorillinite--expandable clay)

Smectite is common only in the thick parting, ranging from absent to the predominant clay mineral. Figures 7B & 7C are typical X-ray traces of smectitic portions of the thick C parting. Major differences in abundance in the thick parting occur both vertically and laterally as discussed below. The other three partings in the C coal bed contain no smectite. A few samples of partings from the A coal bed were examined, and some of these from the thickest parting (8 cm) contained moderate amounts of smectite. It should also be noted that smectite is common to abundant in altered ash partings (bentonites) in tongues of the marine Mancos Shale above and below the Ferron Sandstone Member.

The K-saturation (Weaver) test was performed on one smectitic sample of the thick parting in the C coal bed to determine whether the smectite had a volcanic origin or was derived by degradation of illite-muscovite. Failure of K-saturation to prevent expansion with glycol indicates that this smectite is a low-surface-charge type (volcanic), in contrast to the high-surface-charge varieties produced by weathering of illite-muscovite.

Vertical variations in clay mineralogy

The main variations in clay mineralogy are in the relative amounts of smectite and kaolinite. Relative abundances, expressed as relative X-ray diffraction peak heights, are shown in Table 1. It should be noted that relative peak heights are a poor expression of actual amounts present; however, our concern here is only for relative quantities.

As can be seen from Table 1, kaolinite is generally predominant. On a worldwide basis, kaolinite is almost the only clay mineral present in volcanic ash partings in coals; hence, the relative abundance of smectite in the thick parting is unusual.

Table 1.--Clay Mineralogy and presence of accretionary lapilli in the thick parting, C coal bed, Ferron Sandstone Member, central Utah

[---, not determined]

Station No.	Sample (DMT 79-)	K/S[1]	Q[2]	F[2]	M[2]	Lapilli[3]	Station No.	Sample (DMT 79-)	K/S[1]	Q[2]	F[3]	M[2]	Lapilli[3]
1	40A	2	5	3	1	---	27	147	5	3	1	1	X
	40B	5	3	1	2	---		148	2	5	2	1	0-
	41	5	3	3	3	---	29	152	4	5	2	1	X+
3	50	2	4	1	1	0		153	5	4	1	1	X+
	51	3	5	2	3	X		154	2	5	1	1	0
	52	3	5	1	1	X+	30	159	2	3	1	1	---
4	58	1	4	1	1	X+		[5]160	3	4	1	1	---
	59	1	4	1	1	---		[4]160	3	4	2	1	X
	60	1	5	1	1	0		161	3	4	3	2	X
5	62	2	5	1	1	0	31	165	5	3	1	1	---
6	66	3	4	3	2	X		166	4	4	3	2	0
7	67	2	4	3	1	0	32	170	3	5	2	3	---
11	79	1	3	1	1	0		171	5	5	2	1	0
12	32	2	---	---	1	0		172	5	4	1	1	X
	82	4	3	2	1	0		173	2	3	1	1	0
	83	4	4	2	1	X	33	[5]177	5	4	3	2	---
13	89	2	4	3	1	0		[4]177	3	5	3	3	0
	90	3	3	3	3	X		[5]178	5	4	3	2	X
	91	1	5	1	2	0		[4]178	4	5	3	2	X
14	94B	2	3	2	1	---		179	5	4	1	1	---
	95	3	4	1	2	---		[6]180	3	4	1	1	---
	96	3	3	1	1	---		[7]180	3	5	1	1	0
	97	4	3	1	1	---	34	182	2	3	2	1	0
15	105	5	4	2	1	0		183	3	5	1	1	---
	106	5	4	3	1	X	36	191	2	4	3	1	0
	[4]108	3	3	1	1	X		192	3	4	1	1	X
	[5]108	4	3	5	1	X		193	3	5	1	1	0
23	124	1	3	1	1	X	37	197	1	3	2	1	0
24	130-1	1	3	2	1	0		198	3	3	2	3	X
	130-2	1	4	1	1	0		199	3	4	3	3	X
	130-3	1	3	1	1	---	40	209	3	3	1	1	0
	130-4	1	4	1	1	---		210	3	5	3	2	0
25	134	1	5	3	1	0		211	3	5	2	2	---
	135	1	3	1	1	---	41	216	2	4	1	3	---
26	[5]138B	2	4	1	1	---		217	3	4	1	3	0
	[4]138B	2	5	1	2	0		218	2	3	2	3	0
	139	4	5	1	1	---	43	221	1	5	3	1	---
	140	4	4	1	1	0		221	2	4	2	2	0
	141	2	4	1	1			222	2	3	1	2	0
27	146	3	4	1	1	X+		223	2	4	1	3	0

[1] Relative abundance of kaolinite and smectite, based on simple peak heights (vertical chart units). These values do not reflect absolute abundances because smectite has a greater diffracting power than kaolinite because of form factor.
- 1 = all kaolinite
- 2 = kaolinite >>smectite
- 3 = kaolinite > smectite
- 4 = Kaolinite ≅smectite
- 5 = smectite > kaolinite
- 6 = smectite >> kaolinite
- 7 = all smectite

[2] Abundance of quartz (Q), feldspar (F), and biotite mica (M). Relative intensities (vertical units) based on simple peak heights, diffraction patterns of bulk samples. Kaol. peak at 3.25°A, quartz peak at 3.18°A.
- 1 = absent
- 2 = <5
- 3 = 5-20
- 4 = 21-50
- 5 >50

[3] 0 = looked for but not found.
X = detected.
X+= abundant.

[4] Light, coarse-grained portion.

[5] Dark, fine-grained portion.

[6] Gray portion.

[7] Dark, coaly portion.

In a vertical sequence of samples from a given outcrop of the thick parting, smectite tends to be more abundant near the middle. This was true in every case (16 locations) where such comparisons could be made on a minimum of three samples (top, middle, and bottom). In five localities where fewer than three samples were taken, results are in agreement with the above generality.

Lateral variations in clay mineralogy

Smectite is absent or less abundant at a series of localities in Miller and Muddy canyons where the top of the C coal has been partially eroded, in some cases down to and through the thick parting. Here a marine sandstone rests either directly on the coal bed or on the thick parting. Near the intersection of Muddy and Miller canyons (Station 24), the thick parting has been reduced to a coarse breccia or rubble, probably due to erosion by waves and currents prior to deposition of the overlying sandstone. No smectite is present either in the blocks of rubble or within the thick parting here.

Elsewhere, a general relationship also exists between the thickness of coal overlying the thick parting and the abundance of smectite. In Quitchupah Canyon, for example, six localities with a thick coal interval (115-220 cm) above the thick parting are characterized by abundant smectite. The two northernmost localities have only 41 and 45 cm of coal above the thick parting, and the parting at these localities tends to have less smectite.

At the I-70 roadcut outcrops (one of the more southerly localities), the thick parting is overlain by relatively thick coal (129 cm) but contains only relatively minor smectite, except in the middle part. In this case, however, the thick parting is near the base of the coal bed, and the important factor here may be the presence of a relatively thin coal interval below the parting.

These relationships suggest that the degree of leaching by ground water controls the amount of smectite developed in these partings. The thinner

partings are easily leached, and all soluble cations are flushed out in the leach water, leaving only the less soluble silicon and aluminum to form kaolinite. In thicker partings, incomplete leaching in the middle portion, because of permeability reduction due to clay formation, allows retention of cations and subsequent formation of smectite. Sandstones are good aquifers and, where they are in proximity to the thick parting, the latter is more completely leached and smectite either does not form or is at most a very minor component.

NON-CLAY MINERALS

The non-clay minerals quartz, feldspar, biotite, and various weathering products were identified by X-ray diffraction. All samples were X-rayed in bulk; some were also X-rayed after washing--a process that removes most of the clay and concentrates the coarse, nondispersable portion. Quartz, feldspar, zircon, and magnetite/ilmenite were identified by microscopic examination of washed samples.

Quartz

Next to the clay minerals kaolinite and smectite, quartz is the most abundant constituent of the thick parting. A map of the geographic distribution of quartz abundance in the thick parting only revealed that the quartz content is highly variable, ranging from a trace to a major component. Similarly, the other three partings contain highly variable amounts of quartz without any apparent geographic pattern.

Most quartz occurs as clear, colorless grains with equant, angular shapes. Less common are thin, slivery, splinter-shaped crystals. β-quartz is rare, but nearly every sample contains a few crystals (Fig. 8); most are rounded (resorbed) and very few are euhedral. β-quartz tends to be finer grained than the equant angular type.

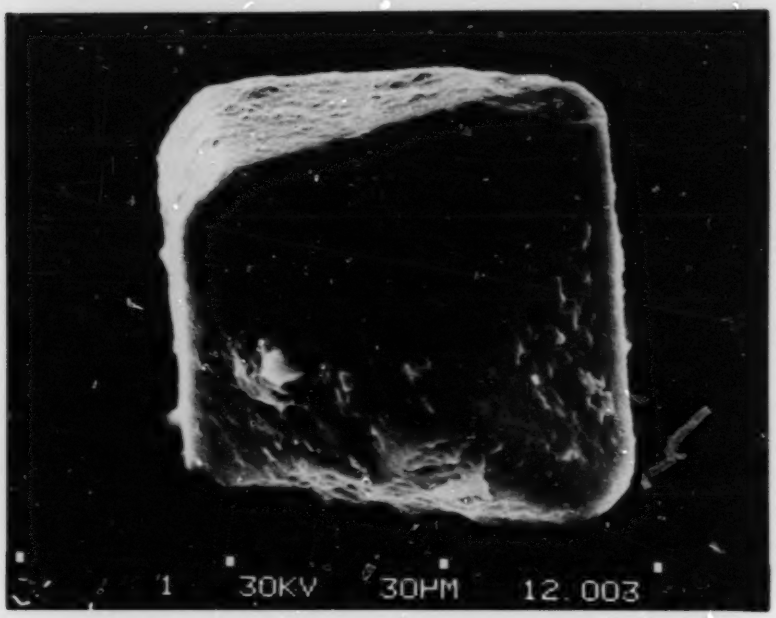

FIG. 8. EUHEDRAL BETA-QUARTZ CRYSTAL.
Tick marks are 30 microns apart

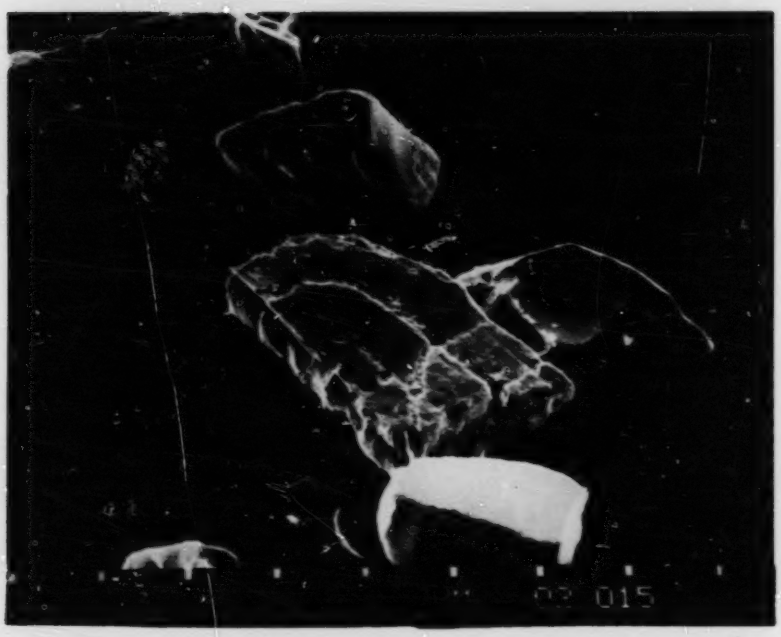

FIG. 9. PLAGIOCLASE AND SANIDINE GRAINS.
Tick marks are 100 microns apart

It's questionable if all of the quartz is in relatively coarse grains (phenocrysts) or if some may be in a fine-grained form of secondary origin. Although one can't be sure, the relatively soft nature of most samples argues against any large amount of secondary silica cement.

The vertical distribution of quartz at sixteen localities in the thick parting shows a distinct lack of quartz near the middle of the thick parting. Seven localities showed most of the quartz at the top, eight showed most of the quartz at the bottom, and only one locality showed the greatest abundance of quartz in the middle. Maximum concentrations of coarse, phenocrystic grains of quartz at the bottom would be understandable, because ash falls are frequently graded with the coarsest material at the base. No clear evidence was found that the thick parting is graded, however, and even if it were, this would not explain the abundance of quartz at the top. As noted in the previous paragraph, there is a possibility that some of the quartz is secondary; this may be the case here, but we have no evidence to support such a suggestion. The occasional abundance of quartz at the top of the thick parting may also be due to winnowing and/or reworking of the original ash layer by wind or water prior to the resumption of peat accumulation.

Feldspar

Based on X-ray diffraction criteria, thin-section observations, and dispersive X-ray data from the SEM, sanidine is the most abundant feldspar in the thick parting. Two samples contained plagioclase, as indicated by albite twinning observed under the petrographic microscope and by a Ca-Na composition (rather than K) of individual grains, as determined by energy dispersive X-ray analysis.

Figure 9 shows both sanidine and plagioclase in a sample of the thick

parting. The single plagioclase grain is in the lower middle part of the photo; all other grains are sanidine. Note that the plagioclase crystal shows pitting and other surface roughness features, as compared to the smooth surfaces of the sanidine grains. This suggests relatively greater susceptibility of the plagioclase to weathering. Also, the curved groove etched in the plagioclase suggests the presence of compositional zoning, a feature restricted to volcanic plagioclase. It should also be noted that sanidines do not always display "textbook" lath shapes or even well-developed crystal faces; therefore, attempts to distinguish sanidine from quartz on the basis of shape were not always successful. However, on rare occasions euhedral sanidine crystals were observed, as is shown in Fig. 10. Figure 11 illustrates a sanidine crystal (rounded by corrosion) that clearly displays the presence of twinning according to the Carlsbad law. The central "mirror image" twin plane is more deeply eroded, resulting in a joined pair of crystals.

Feldspar X-ray peaks are never as intense as quartz peaks, probably reflecting a predominance of quartz over feldspar. Because feldspar tends to be lost during diagenesis, however, it is not certain what its original abundance was relative to quartz.

There is some tendency for feldspar to be concentrated toward the bottom of the thick parting. This conclusion is based on X-ray diffraction peak heights for multiple vertical samples from a given locality. At 19 localities, the occurrence of maximum feldspar was as follows: 10 at the bottom, 5 in the middle, and 4 at the top. Note that these are relative values; in terms of actual measured peak heights, feldspar distribution appears to be somewhat erratic. Mostly it appears as a minor component on X-ray traces, but in five instances it appears as a significant component. Such instances should be regarded with caution, because feldspar is subject to

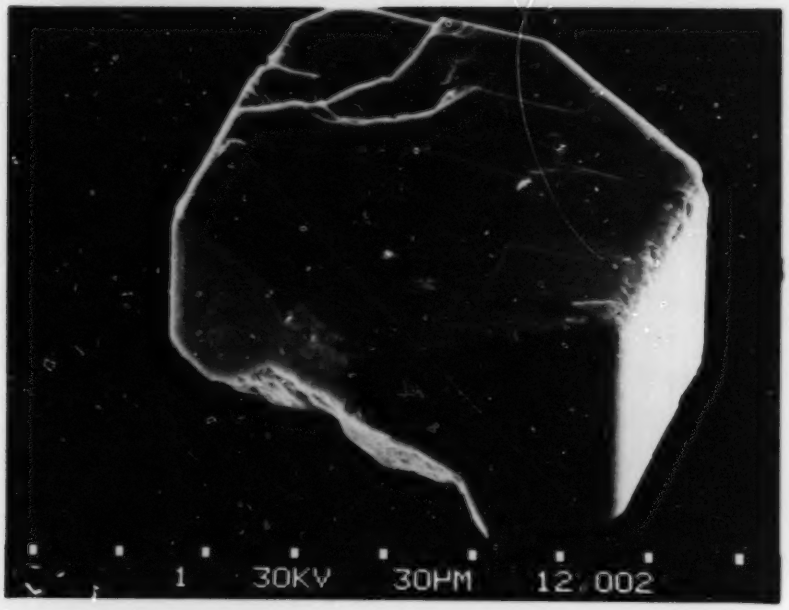

FIG. 10. EUHEDRAL SANIDINE. NOTE CRYSTAL FACES.
Tick marks are 30 microns apart

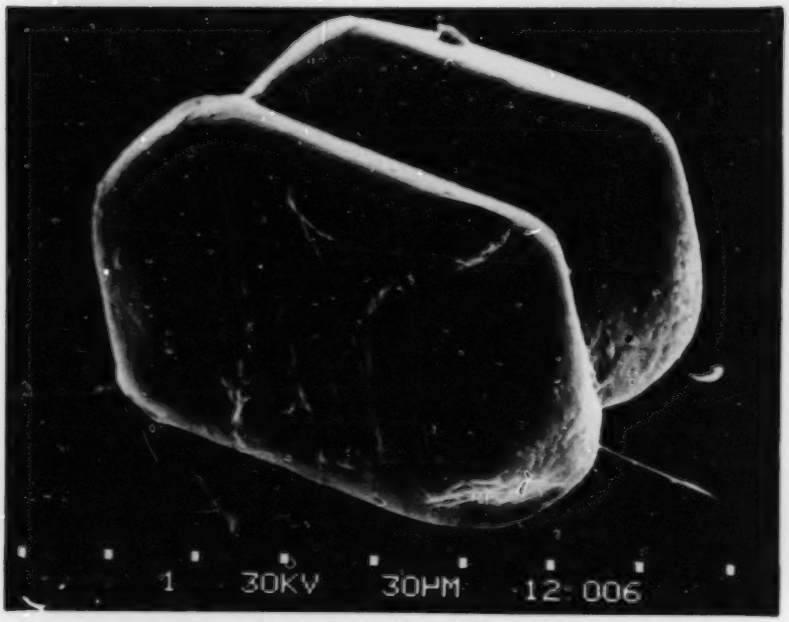

FIG. 11. TWINNED SANIDINE CRYSTALS.
Tick marks are 30 microns apart

strongly preferred orientation, and a single grain, fortuitously oriented, can give a strong reflection. Bearing all this in mind, no pattern can be seen in the lateral distribution of feldspar, but the vertical variation noted is probably valid.

The abundance of feldspar in sand-filled burrows in blocks and partially eroded layers of the thick parting in Miller Canyon is of interest. The ash parting itself contains no detectable feldspar, but feldspar, in at least minor amounts, occurs at equivalent levels at other nearby locations. This distribution suggests that destruction of feldspar in the thick parting occurred while it was enclosed in coal and before it was exposed to erosion (and prior to the deposition of the overlying sandstone).

Some further comments may be made regarding feldspar. No feldspar was detected in the other three partings of the C coal bed. This may reflect its absence in the original ash or, more likely, the more intense alteration of these thinner partings. An I-coal parting, from a core being studied by Jean Minkin (USGS, Reston), contains abundant plagioclase feldspar identified as andesine (Ca-Na) by elemental analysis. Our SEM photos, energy dispersive X-ray analysis, and X-ray diffraction analyses confirm her identification. This distinctly different feldspar composition in a coal zone above the C coal bed may indicate a volcanic source different from that which erupted the C-coal ashes.

Biotite (mica)

For purposes of this discussion, all 10Å material in X-ray diffraction patterns is assumed to be biotite mica; that is, volcanic mica of relatively coarse grain size. The presence of clay-sized 10Å material of illitic (muscovitic?) affinities is uncertain, since we have examined only bulk samples. In support of this assumption, R. Pollastro (USGS, Denver, oral

communication, 1980) encountered a similar occurrence of coarse biotite in a marine altered volcanic ash (bentonite). In this case the clay-size fraction contained little or no 10Å material.

Biotite is nowhere abundant in the thick parting and is entirely absent in almost all samples collected north of the junction of Miller canyon and the canyon of Muddy Creek. Southward, it is intermittently present; the southernmost two samples contain the maximum amount of biotite. It is absent from the other three partings in the C coal at all locations.

Where it is present, there is a slight tendency for biotite to be more abundant toward the base of the thick parting. At seven localities, maximum biotite occurs at the base; at two localities the maximum amount is in the middle; and at one locality the same quantity occurs at the middle and top with a lesser quantity at the bottom. Note, however, that these locations are only 10 out of a total of 26, the other 16 locations contained no detectable biotite in X-ray traces from bulk samples.

Biotite commonly has altered to kaolinite in the thick parting, the degree of alteration ranging from slight to complete. Where alteration is complete, the result is a kaolinite pseudomorph after biotite; such grains appear as thick flakes, and many retain the original hexagonal shape (Fig. 5, p. 8). Where alteration of biotite stacks is incomplete, the centers of flakes remain dark and unaltered, while the edges are white or silvery. Alteration to kaolinite involves some swelling, and bloated, barrel-shaped grains are common. Where only the edges have been altered to kaolinite and thus expanded, the resulting grains are disk-shaped, with expanded edges surrounding an unexpanded center.

Zircon

Zircon was observed in washed samples (coarse fractions) by panning the heavy minerals to the edge of grain concentrates. Quantities were too small

to be detected by X-ray diffraction of bulk samples.

Zircons were found in nearly every sample (Fig. 12). Because there is much variation in the degree to which clays are removed by washing, microscopic observations on the relative abundance of zircon are questionable. Zircons are probably uniformly present in trace amounts.

Other Minerals

Trace quantities of black, opaque metallic grains were observed in about one-fourth of the samples from the thick parting. Many of these grains were euhedral, with very smooth, shiny crystal faces (Fig. 13). Although all are generally similar, some react to a magnet, others do not. Based on their general appearance and the detection of Ti and Fe by energy dispersive X-rays on the SEM, these crystals are tentatively identified as magnetite/ilmenite. In some cases magnetite/ilmenite has been altered to leucoxene (white in reflected light). In other cases, grains of identical shapes are composed of a reddish-brown nonmagnetic material; these are probably siderite or iron-oxide pseudomorphs.

Traces of pyrite as isolated cubes or angular masses were observed in samples from three localities. In at least two of these localities, the C coal bed is directly overlain or even partly eroded by marine sandstone. The pyrite may be related to the proximity of marine waters, but the number of samples is too small to enable any firm conclusions to be made.

Dolomite occurs in the thick parting at a number of locations. As with pyrite, there appears to be a relationship to the proximity of an overlying marine sandstone. Dolomite generally occurs in trace quantities, but somewhat larger amounts occur in samples 140 and 171; in these cases, reddish-brown crystals could be panned out with other heavy minerals.

Calcite was only observed in trace quantities in two samples.

FIG. 12. IDIOMORPHIC ZIRCONS.

Tick marks are 100 microns apart

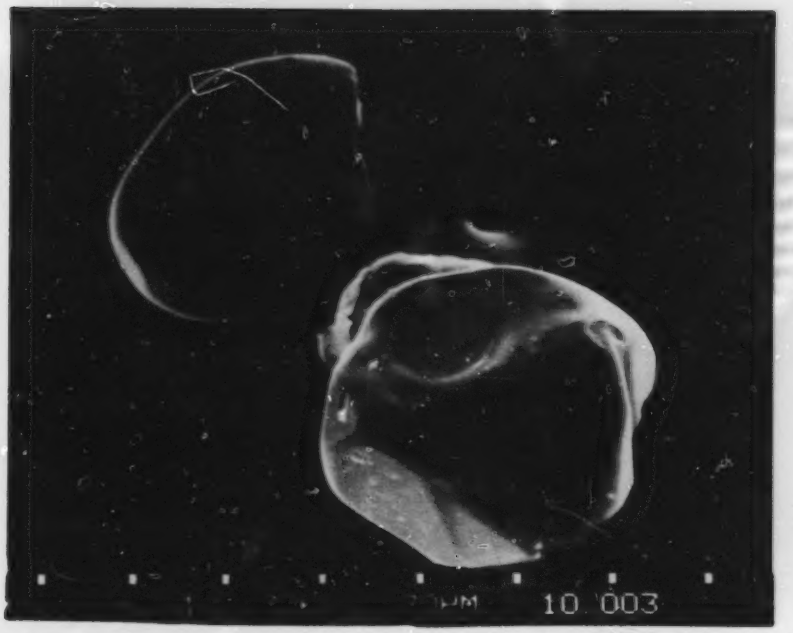

FIG. 13 MAGNETITE / ILMENITE.

Tick marks are 30 microns apart

Various weathering products, such as jarosite, gypsum, limonite, and melanterite, were detected, but no systematic observations of these minerals were made.

Apatite was only observed in the thick parting where it was sampled out of coal, enclosed within the equivalent shale, far to the south at Last Chance Canyon. It presumably was originally present everywhere in the thick parting, but was lost in solution where the parting is enclosed in coal due to the presence of organic acids.

Dark, organic-rich volcanic ash partings

Most volcanic ash partings are light colored. Those that are dark weather to light colors. However, part of the thick parting commonly is so organic-rich that it remains dark even when weathered and sometimes is not readily distinguished from the adjacent coal.

At 17 locations the dark part of the thick parting occurs at the top, at 2 locations it was at the bottom, and at 11 locations the thick parting is uniformly light colored. The contact between light and dark parts is usually very sharp. The light part is usually almost structureless, but the dark part commonly shows irregular color and textural differences, probably the result of organic activity (plant growth), slumping, or other types of flowage during compaction.

The mineralogy of the light and dark parts of the thick parting was compared at about 20 locations with the following results:

(1) There is a strong tendency toward less smectite and biotite in the dark part, but is this because it is dark or because it is at the top? Sample 223 is from dark material at the base of the parting and contains more biotite than samples from the overlying light-colored portion. This suggests that the distribution of biotite is related to vertical size grading, rather than to the dark color.

(2) No particular pattern exists in the distribution of quartz and feldspar.

The thickness of the dark part is variable and can change abruptly. At 19 locations it ranges between 2.5 and 23 cm, with an average thickness of 10.4 cm. At an abandoned mine in a tributary to Miller Canyon (Station 30), the thickness of the dark and light parts changes significantly from one side of the mine mouth to the other, a distance of perhaps eight feet. On the left side 16 cm of dark material overlies 15 cm of light material; on the right side 13 cm of dark material overlies 26 cm of light material.

The thinner partings also show lateral variations in organic content and color, but the changes are not as dramatic as those of the thick parting. Also, they seem to differ in the nature and distribution of the organic matter. Organic matter in the thinner partings tends to consist of scattered coaly particles, while the dark portion of the thick parting contains very little actual coal, the dark color being related instead to finely divided organic material intimately mixed with clay.

The origin of the dark material of the thick parting and the processes that produced its various characteristics are unknown.

THICKNESSES OF COAL INTERVALS AND PARTINGS

Thicknesses of the coal intervals and the partings (Table 2) have been recorded at 46 localities, including 16 studied by previous workers (mainly R. Phillips and T. Ryer, 1977-78). Additional thickness measurements will be obtained from a series of cores taken during the spring of 1980. It is hoped that all of this information eventually can be compiled for a series of isopach maps.

Even though no maps showing thickness variations are included in this report, examination of the limited data available permit some general comments.

Table 2.--Thicknesses of altered volcanic ash partings and intervening coal intervals of C coal bed, Ferron Sandstone Member, central Utah

Station No.	Thicknesses (centimeters)								
	Volcanic ash partings			Coal Intervals					
	Thick	U. Doub.	L. Doub.	Lower	Top to Thick	Thick to U.Doub.	Between U & L doublet	Doub. to Lower	Lower to base
EE-4 (M-15a) (eroded)	15.2	5.2	4.9	6.1	12.2	55.7	43	61	33.5
100′ upstream from EE-4	eroded	3	4.6	5.2	eroded	---	37.5	62	22.2
300′ upstream from EE-4	36.6	3.7	3.7	7.6	45.7	48	40.3	47.3	51.8
MB-1	36.6	7.6	1.5	8.2	143.2	56.4	10.7	71	73.2
EE-5 Grassy Valley	32	1.5	2.4	4.3	19.8	52.2	26.8	50.6	---
12	33.5	2.1	---	4.9		52.4	---	73.6	68.6
MB-5 (sec. P-1-77) (eroded)	13.7	1.5	1.8	6.1	eroded	57.9	2.8	61	79.2
MB-6 (Bear Gulch)	50	3.7	3.7	6.1	127	59	8	48	65.5
Bear Gulch mine (few 100′ east--all but 20 cm of coal above thick is eroded)	eroded	6.1	1.8	10.4	eroded	---	20.8	50.6	94
MB-7	35	3	3	6.1	125	64	9.2	64	88.4
MB-8	39.6	3.6	3.6	13.7	49	123	10.1	47.3	205.7
MB-9	60	7	7	8	125	68	23	37	90
	25								
WF-1	49	2.4	3.7	6	114	72	22	56	---
WF-2 (Ivie Crk.)	37	1.5	---	6	3-4	82			
WF-3	27	---	---	---	274	Thick parting is at base of coal			

Table 2.--Thicknesses of altered volcanic ash partings and intervening coal intervals of C coal bed, Ferron Sandstone Member, central Utah--Continued

Station No.	Thicknesses (centimeters)								
	Volcanic ash partings				Coal Intervals				
	Thick*	U. Doub.	L. Doub.	Lower	Top to Thick	Thick to U. Doub.	Between U & L doublet	Doub. to Lower	Lower to base
1	40(9)	5	2	10	44	55	25	130	
2	eroded	5	3.5	12		45+(eroded)	5	65	58
3	28(12)	7	2	16	8	60	3	64	40+
4	30(10)	5.5	4.5	---	29	55	5	---	---
5	40(10)	6.5	2.5	15	40	~50	6	---	~75
6	40(12)	---	---	---	30	---	---	---	---
7	39(18)	---	---	---	19	---	---	---	---
8	15+(eroded)	6	3	13+	---	58	6	58	~55
11	9	---	---	---	---	---	---	---	---
13	35(8)	~1	3	4	25	46	22	60	---
14	36.5(12)	3.5	---	15	30	45	10	55	---
15	16+(eroded)	6	2.5	13	---	57	6.5	60	
16	36(14)	4	7	20	7	~50	6	58	~50
21	breccia	---	---	---	---	---	---	---	---
22	breccia	12	6	12	---	57+(eroded)	6	69	65
23	9-12+(eroded)	4+	---	10.0	---	67	---	---	---
24	16+(eroded)	6	4	8+	---	58	6	55	59
25	20(max)	3	4.5	13	5	40	3.5	66	60
26	34(7)	6	4	12	143	62	10	73	73
27	48(16)	5	4.5	---	124	46	10.5	46	68
29	56(14)	10	4.5	8	160	63	13	52	90
30	39(15)	5	5.5	16+	23	61	8	---	50+
32	58(10)	8	5.5	6	115	62	26	46	93
33	68(12)	2.5	17	17	220	70	34	26	~75
34	45	6	10	9.5	~170	65	27	32	60
36	50(10)	6	4	16	45	58	18	43	60
37	27(6)	8	5	10	41	63	18	42	69
40	56(23)	---	---	---	180				
41	34	---	---	---	129	23 cm coal between base of thick bottom of C			
43	48(8)	---	---	---	60	2 cm coal below thick to base of C			

*Nos. in parentheses are thicknesses of dark-colored portion of thick parting.

First, there is some ambiguity in the measurements of the thicknesses of the partings. The thick parting generally has sharp, readily identified contacts with the enclosing coal beds. The other partings, however, sometimes have sharp contacts, but frequently are so coaly that boundaries are not readily distinguished. In some places, these thin partings may be split into several layers with thin stringers of coal between them. Thus, some of the variation in thickness shown for the three thinner partings may reflect lack of definition of the partings rather than actual thickness changes.

Overall, the main impression gained from examination of isopach data on the partings is that their thicknesses are quite variable. There are no simple trends in recorded thicknesses that indicate the direction or proximity of the source.

The data also suggest that the Quitchupah Canyon area is anamolous. Several of the partings and intervening coal intervals are abnormally thick here. It is not immediately apparent why the thicknesses of coal beds and the ash partings should increase together, since they originated by such different processes.

ACCRETIONARY LAPILLI

Accretionary lapilli (also known as volcanic pisolites, mud pellets, volcanic or fossil hailstones, mud balls, tuff balls) are spheroidal or ovoidal aggregates of volcanic ash, commonly with a fine-grained, darker outer rim, giving a concentric structure in cross section. Their character, geologic distribution, and origin have been summarized by Moore and Peck (1962). The important point here is that they are generally accepted as the product of volcanic eruption, occurring either in base-surge or air-fall deposits.

Accretionary lapilli occur in the thick parting at a number of locations. This is the first reported occurrence of them in partings in coal beds, and provides further evidence for the volcanic origin of the partings. Conversely, the occurrence of partings containing accretionary lapilli in a coal bed far from any known volcanic source indicates that these features are not restricted to deposits near the eruptive center, as was proposed by Moore and Peck (1962). At these presumably great distances from the volcano, the lapilli cannot possibly accrete and be precipitated by means of clouds of steam issuing from the vent, because this steam would have long since dissipated into the atmosphere. Rather, the agent of formation within and deposition from the ash cloud was probably ordinary thunderstorms.

Accretionary lapilli were identified in 23 samples of the thick partings at 16 localities. The geographic distribution probably has little significance, and is thought to be related more to variable preservation factors than to the location of the source. No pattern resembling the linear swath of a storm path could be seen.

Most of the lapilli are on the order of 5 mm in maximum dimension (Fig. 14). They are ovoid when seen in cross sections cut perpendicular to bedding, reflecting compaction. In sections parallel to bedding they are usually circular, but in one sample they were distinctly ovoidal, a feature that is ascribed to soft-sediment flow during compaction.

Compared to examples in the literature, accretionary lapilli here are less well developed in two respects. First, they are usually very faint, to the point that they may be visible only on specially prepared surfaces. Secondly, only one layer of finer, darker material (the outer rim) is present, rather than a series of concentric layers. This means that they are not easy to detect in the field and may not be visible at all on broken rock surfaces,

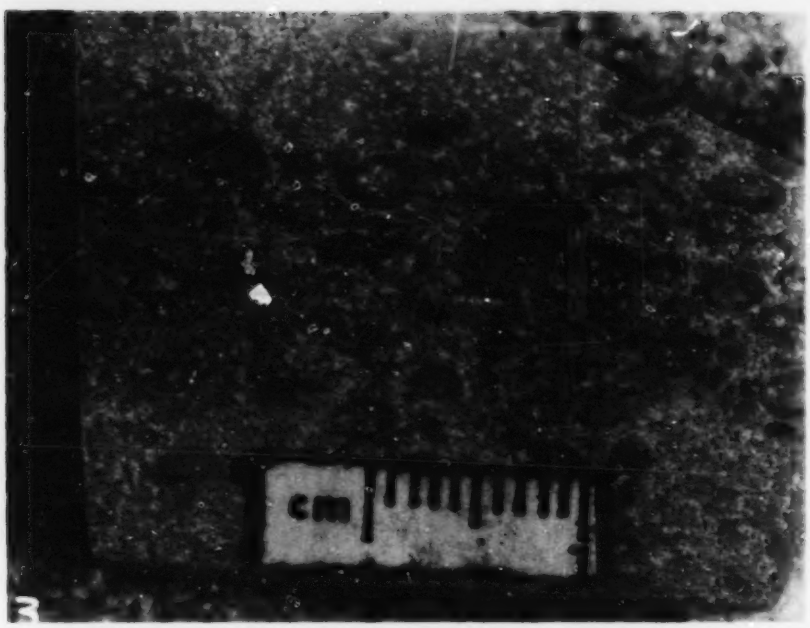

FIG. 14. ACCRETIONARY LAPILLI IN THE THICK PARTING.

particularly when the latter are weathered. The use of sandpaper to smooth rock surfaces and glycerine to provide a wet surface proved very helpful in detecting accretionary lapilli.

It seems likely that accretionary lapilli were deposited widely within the thick parting, but in most places have been obscured or completely obliterated during its alteration to clay. No strong relationships to clay mineralogy or texture are apparent, although such relationships need to be studied more closely. We are not certain what factors favor the preservation of accretionary lapilli; obviously bioturbation, soft-sediment flow, and compaction tend to destroy them.

RADIOMETRIC DATING

Because volcanic ashes consist largely of minerals formed at the same time (but not the same place) as the enclosing coal, radiometric dating of such minerals should provide the age of the coal.

The K-Ar method has been the main technique used for dating volcanic materials. Very little such dating has been done on partings in coal beds, except for studies by Triplehorn and others (1977) in Alaska and by Folinsbee and others (1961) in Canada. Plagioclase, sanidine, biotite, and hornblende have all proven datable. In the C coal bed, only sanidine and biotite in the thick parting are datable; plagioclase occurs only in trace amounts. The thinner partings contain no biotite or sanidine.

Potassium-argon dating has been attempted on minerals from five ash partings. Two samples are from the thick parting in the C coal bed, two are from a parting in the A coal bed, and one (a bentonite) is from the underlying Tununk Shale Member (Fig. 1) of the Mancos Shale.

The dating has been only moderately successful. One sample from the thick parting gave ages of 92 and 103 m.y. on altered biotite and impure

sanidine, respectively. The other thick parting samples gave meaningless results. One sample of sanidine from the A coal bed parting gave an age of about 92 m.y. (in good agreement with the altered biotite from the C coal), but the other sample gave meaningless data. The Tununk bentonite sample gave ages of about 96 and 92 m.y. on altered biotite and sanidine, respectively. These are in reasonable agreement with the A coal bed ages and one of the thick parting (C coal bed) ages. In summary, three ages are near 92 m.y., two ages are slightly older, and two samples proved undatable because of poor mineral separation. The best age of 92 m.y. from this data compares with an age of ~87 m.y. for the late Turonian derived from K-Ar measurements by Obradovich and Cobban (1975).

Several reasons for these poor age data can be surmised. Of major importance is the failure to adequately separate quartz from sanidine, resulting in "sanidine" concentrates with very low K_2O contents. The samples that were undatable contained only about 0.4 and 0.06 percent K_2O; the three successfully dated sanidine concentrates ranged from about 2 to 12 percent K_2O. Thus, impure mineral concentrates and resulting low K_2O contents may be part of the problem.

Similarly, the biotite concentrates for two samples had low K_2O contents (2.7 and 4.6 percent). In this case, the low values are related to loss of potassium due to weathering or diagenesis, rather than to contamination by other minerals.

An attempt is also being made to use fission-track dating of zircons. Experience elsewhere indicates that fission-track ages of zircons from ash partings in coal are less reliable than K-Ar ages (C. Naeser, USGS, oral communication, 1978); the fission-track ages tend to be about 10 percent younger than K-Ar ages. Our work with fission-track dating of partings from

the C coal bed is directed toward finding the reason for the apparently young zircon ages, since this problem seems to be peculiar to coal. Virgil Frizzell, USGS, Menlo Park, is cooperating with us in this study.

THIN-SECTION PETROGRAPHY

Thirty-eight thin sections of the thick parting were examined. So far, this analysis has been proven to be of limited value. A great deal of textural variety occurs, but no meaningful patterns are apparent in terms of geographic distribution or relationship to other properties. Several textural classifications exist, but none of them are entirely satisfactory and there seem to be inadequate bases for developing a new one.

Re-examination of the thin sections at a later stage in the study may be of value. Petrography was one of the first aspects of this study, and much additional information has been developed since then. Even so, we doubt that major discoveries will result. This is based on the voluminous European work that has been concerned primarily with descriptive petrography and the development of textural classification. In our opinion, thin-section study is satisfying and perhaps necessary in that it provides concrete visual images of the textures of the ash partings, but the benefits of such descriptive studies, as such, have already been obtained by other workers. So far the petrographic descriptions haven't helped much in the interpretation of the origin of these partings.

DISCUSSION

Origin

We recognize a volcanic origin for the partings studied here. The following is a summary of the evidence for their volcanic origin. It should be pointed out that there is still some controversy regarding the origin of clay partings in some coal beds, particularly where no direct evidence, such as volcanic glass shards or β-quartz crystals, exists.

Certain partings in coal beds of the Ferron Sandstone Member are thought to be volcanic in origin for the following reasons:

1. Thin, widespread, relatively uniform character with sharp contacts and without evidence of current transport (such as lamination, ripples, scour, lag deposits, or crossbedding).
2. The marked bimodal size distribution of some samples; that is, sand-sized grains irregularly scattered through a clay-sized matrix.
3. Presence of a limited mineralogical suite, some members of which are primarily volcanic in origin:
   a. Euhedral β-quartz forms.
   b. Splinter-shaped quartz.
   c. Sanidine (sometimes lath-shaped or euhedral).
   d. Euhedral zircons.
   e. Euhedral magnetite/ilmenite.
   f. Euhedral biotite crystals.
4. Presence of accretionary lapilli.
5. Monomineralic clay mineral composition of some samples (detrital terrigenous suites are always heterogeneous).
6. Presence of bentonites in associated marine shales (which are more readily recognized than their equivalents in coal, and whose volcanic origin is widely accepted) proves that explosive volcanism was occurring about this time.
7. Radiometric age determinations that are nearly concurrent with the known stratigraphic position and paleontological age of the Ferron Sandstone Member (terrigenous detrital minerals would yield ages that are much too old and probably highly variable).

The above list includes factors that provide strong evidence for the origin of these partings as air-fall volcanic ashes that were deposited in a swamp. Their existence in continuous layers argues that they fell into water no more than a few feet in depth. If they had fallen on a subaerial surface, they would have been subsequently eroded; if the water had been more than a few feet deep, rooted plants would have been unable to grow and the environment would have been a lake, probably with terrigenous detrital sediments, rather than a coal-forming swamp.

The factors of low relief, shallow water, and the baffling effects of plants all retarded the redistribution of the ash or the introduction of terrigenous clastic (stream-flood) deposits. Following ash deposition, plant growth was re-established and peat accumulation resumed. This resulted in each ash layer being isolated and preserved within a matrix of organic material.

Postdepositional changes in the ash partings were severe, probably because of the highly acid conditions and vigorous biological activity of the peat swamp. Compounds released during mineral alteration were largely flushed out by ground water and surface water movement through the peat. In terms of quantity, silicon was the most important material lost, but soluble ions such as the alkalis and alkaline earths also were almost entirely removed.

Reasons For Differences in Mineral Composition

The three thinner partings of the C coal consist of kaolinite and quartz, and little else. The thick parting shows considerable vertical as well as lateral variation in minerology, and these differences will now be considered.

The main factors controlling mineral composition are the original composition of the ash and postdepositional conditions in the peat swamp. As

noted above, the leaching of Si and other cations accompanies the alteration of glass and other susceptible minerals to kaolinite and smectite. In this context it appears that the thickness of the original volcanic ash layer may influence the speed or effectiveness of leaching, and thus directly influence the resultant mineralogy. The thick parting is thought to differ from the others mineralogically because it is thick. The apparent end product of extensive leaching is kaolinite and the resistate volcanic minerals, such as quartz and zircon. This is the case with the thin partings and, generally, with the top and bottom of the thick parting. Commonly, however, the interior part of the thick parting contains significant smectite, sanidine, and biotite, signifying the retarded effectiveness of leaching in thick units.

Effectiveness of leaching is not simply a matter of thickness, however. The proximity of permeable beds also appears to be a factor for the thick parting. Where a sandstone directly overlies the C coal bed, in some cases cutting into the upper part of the bed, the thick parting lacks smectite, biotite, and feldspar, even though these are present in most other places within the thick parting. The most instructive series of outcrops occur in Miller Canyon, south of the Casper Mine. Here a No. 4 delta-front sandstone rests erosionally on top of the coal, cutting progressively downward to the south until the sandstone lies directly on the thick parting. Further south, the thick parting is largely replaced by sandstone, being reduced at one point to a rubble or lag deposit of broken blocks, and then is lost entirely. Throughout this area, the thick parting consists only of kaolinite and quartz; smectite, biotite, and feldspar are not present, presumably due to the more effective leaching related to the proximity of the permeable sandstone.

Previous studies also have related the difference of clay mineralogy within altered volcanic ashes to the thickness of the deposit. Morgan and others (1979) suggest that for a Cretaceous fuller's earth "the extent of kaolinization appears to have been controlled mainly by the thickness of the bed." Similarly, Šrodoň (1976) presents a model for the progressive kaolinization of volcanic ash layers, mainly bentonites. He notes (p. 67) that "almost completely kaolinized rocks (tonsteins) have been encountered only within coal seams...," in one case only the top and bottom of such a parting in coal. Thus, such a model seems relatively well established, even though the details remain to be worked out.

Time of Alteration of the Ash Partings

Arguments can be presented that both the physical and chemical-mineralogical variations in these partings were developed relatively early.

The exposures in Miller Canyon, whose mineralogical variations have just been described, are most instructive. The rubble, or lag deposit, formed by angular, rotated blocks of the thick parting indicate that, in the time interval between deposition of the volcanic ash and deposition of the overlying sandstone, physical and mineralogical changes of the thick parting were essentially completed.

From a physical standpoint, it is apparent that the thick parting was cohesive, or even brittle. It was firm enough for animals to form burrows in it and firm enough to break up into angular fragments along planar fractures. The undistorted forms of the angular fragments and the enclosed burrows shows that there was little or no later compaction and, by inference, no significant leaching or loss of mass.

The contrast between the mineralogy of the blocks of the thick parting and that of the sand-filled burrows provides further evidence that the mineralogical transformation was essentially complete at this time. The sand-filled burrows are very feldspathic, but feldspar is completely missing in the enclosing matrix of the thick parting. The presence of feldspar elsewhere in the thick parting suggests that it was probably present here originally but was later destroyed. It appears that feldspar (and probably also biotite) in the thick parting were lost before the burrowing occurred. The precise length of time involved cannot be determined, but it seems likely that lithification of the partings was essentially completed in no more than a few thousand years, perhaps much less.

Similar evidence has been used by others to argue that the alteration of volcanic ashes to clay minerals occurs quickly. Sfodón (1976) noted calcite concretions in bentonites that could only have formed while the material was soft, and yet must be younger than the formation of kaolinite. He concludes (p. 66) "the process of clay minerals formation...may be limited in time to the period of early diagenesis, immediately after deposition of the sediment...." Burger (1966) observed brittle fracture of tonsteins that must have occurred very early because the immediately overlying parts of the same unit have normal stratification. He concludes (p. 44) "This means by this time the formation of the kaolinite [morphological types]...had been completed, because in the section they exist fully developed." And further, "They reveal that the process of formation...does not take place slowly, but extremely quickly, having been almost completed in the state of early diagenesis."

CONCLUSIONS

This detailed study of the partings in the C coal bed of the Ferron Sandstone Member has revealed that they originated as vitric volcanic ash falls that rapidly altered to their present claystone lithology in the acidic waters of the peat swamp. The thin, well-flushed partings altered to kaolinite, while the thick parting became kaolinized only at its top and bottom portions, the center altering instead to smectite because of restricted flushing and leaching. The proof that these partings had such an origin lies in the distinctively volcanic character of their non-clay mineralogy and the presence of accretionary lapilli in the thick parting.

The sanidine component of these partings allows them to be dated by the K-Ar method. Poor results on these partings were due at least in part to incomplete mineral separation prior to radiometric analysis.

References

Bartram, J. C., 1937, Upper Cretaceous of Rocky Mountain Area: Am. Assoc. Petroleum Geologists Bull., v. 50, p. 2185-2196.

Burger, K., 1966, Tur entstehung der kaolinit-formentypen (graupen und kristalle) in kaolin-kohlen-tonsteinen: Geologische Mitteilungen, v. 6 (Breddin Festschriff), p. 43-86.

Cotter, E., 1975, Deltaic deposits in the Upper Cretaceous Ferron Sandstone of Utah, in Broussard, M. L., ed., Deltas, models for exploration: Houston Geological Society, Houston, Texas, p. 471-484.

_____1976, The role of deltas in the evolution of the Ferron Sandstone and its coal: Brigham Young University, Geology Studies, V. 22, part 3, p. 15-41.

Davis, L. J., 1954, Stratigraphy of the Ferron Sandstone: Intermountain Assoc. Petroleum Geologists Guidebook, 5th Annual Field Conf., p. 55-58.

Folinsbee, R. E., Baadsgaard, H., and Lipson, J., 1961, Potassium-argon dates of Upper Cretaceous ash falls, Alberta, Canada: Annals New York Acad. Science, v. 91, p. 352-359.

Hale, L. A., 1972, Depositional history of the Ferron Formation, central Utah, in Plateau-Basin and Range Transition Zone, central Utah: Utah Geological Assoc. Pub. No. 2, p. 29-40.

Katich, P. J., 1954, Cretaceous and early Tertiary stratigraphy of central and south-central Utah with emphasis on the Wasatch Plateau area: Intermountain Assoc. of Petroleum Geologists, 5th Annual Field Conference Guidebook, p. 42-54.

Lupton, C. T., 1916, Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U.S. Geological Survey Bull. 628, 84 p.

Moore, J. G. and Peck, D. L., 1962, Accretionary lapilli in volcanic rocks of the western continental United States: Jour. Geol., v. 70, no. 2, p. 182-193.

Morgan, D. J., Highley, D. E., and Bland, D. J., 1979, A montmorillonite, kaolinite association in the Lower Cretaceous of south-east England: International Clay Conf., Developments in Sedimentation, 27, p. 301-310.

Obradovich, J., and Cobban, W., 1975, A time-scale for the late Cretaceous of the Western Interior of North America: Geol. Assoc. Canada, Special Paper Number 13, p. 31-54.

Ryer, T. A., 1979, Deltaic coals of Ferron Sandstone Member of Mancos Shale--Predictive model for Cretaceous coals of Western Interior [abs.]: Am. Assoc. of Petroleum Geologists Bull., v. 63, p. 519.

Ryer, T. A., Phillips, R. E., Bohor, B. F., and Pollastro, R. M., 1980, Use of altered volcanic ash falls in stratigraphic studies of coal-bearing sequences: An example from the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale in central Utah: Geol. Soc. Am. Bull., part 1, v. 91, p. 579-586.

Środoń, J., 1976, Mixed-layer smectite-illites in the bentonites and tonsteins of the Upper Silesian coal basin: Polska Akad. Nauk, Oddzial Krakowie, Kom. Nauk. Mineral., Prace Mineral., no. 49, 84 p.

Triplehorn, D. M., Turner, D. L., and Naeser, C. W., 1977, K-Ar and fission-track dating of ash partings in Tertiary coals from the Kenai Penninsula, Alaska: A radiometric age for the Homerian-Clamgulchian Stage boundary: Geol. Soc. Amer. Bull., v. 88, p. 1156-1160.

PLATE 1.--MAP SHOWING SAMPLING STATIONS OF

C COAL, FERRON SANDSTONE MEMBER.

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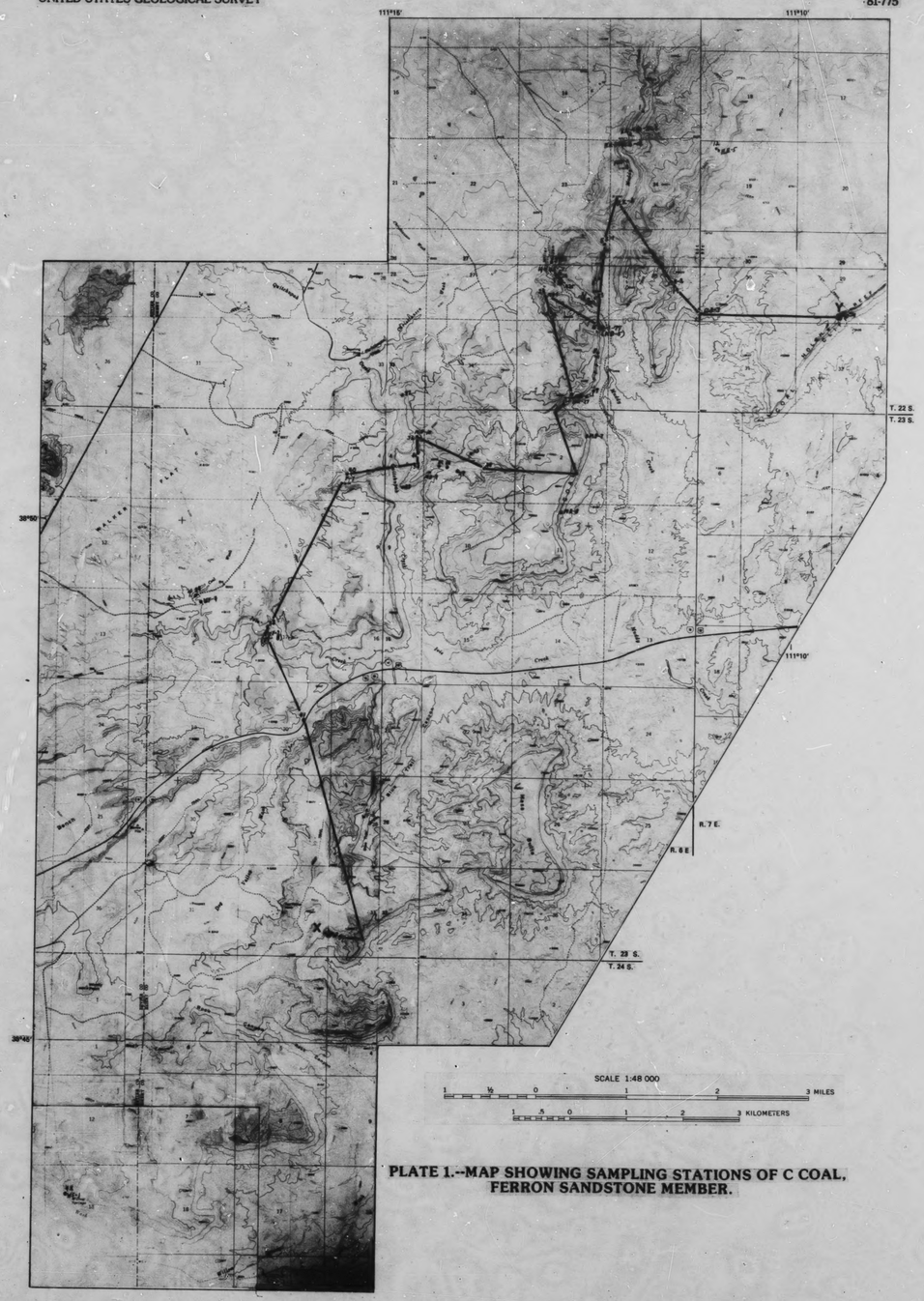

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

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PLATE 1.--MAP SHOWING SAMPLING STATIONS OF C COAL, FERRON SANDSTONE MEMBER.